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Empirical methods for converting rainfall rate distribution from several higher integration times into a 1-minute integration time in Malaysia

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The rapid development of the radio communications system, especially in developed countries, has drawn the attention of telecommunication systems engineers to explore the frequency band above the K_u band. Because radio communication systems operating in the frequency band above the K_u band (10 GHz) suffer from rain attenuation during rainy conditions, prediction of rain attenuation using a 1-min rainfall rate distribution is indeed vital. However, a 1-min rainfall rate distribution is not widely available compared to rainfall rate distributions with longer integration times. Therefore, a suitable conversion method is required to predict 1-min rainfall rate distributions of distinct integration times. This paper presents several conversion methods such as Segal, Burgueno et al., Chebil and Rahman, Joo et al., EXCELL RSC and LG. The Segal method provides an overall Root Mean Square (RMS) error below 5% at different integration times and is suitable to be used in Malaysia.

Keywords: integration time, rainfall rate distribution, conversion method, conversion coefficient, microwave

1. Introduction

In recent years, the rapid development of technology for wireless communications, especially in developing countries, causes the frequency bands to reach a saturated level. Because of this issue, telecommunication systems engineers are exploring the frequency band above the K_u band (10 GHz) in order to meet the rapidly growing request for wide bandwidth for transformation of the tricky radio access network. The frequency band above 10 GHz is advantageous because it provides a wider spectrum and potential repeated use of frequencies and because the size of aerial and equipment is compact. Unfortunately, in the frequency band above 10 GHz, the electromagnetic signals are faded due to rain drops in rainy conditions. This is because as the frequency increases, the wavelength of the signal decreases and the rain drops affect the propagation of the signal. Rain drops disturb the propagation of an electromagnetic signal in three ways: rain attenuates the signal, alters the signal polarity, and increases the system's noise temperature (Mandeep et al., 2007).

To resolve the effect of fading, an accurate estimation of the rain-influenced fading effect on the propagation rate of electromagnetic signals using a 1-min rainfall rate is significant. The International Telecommunication Union (ITU) silently approves the use of a 1-min integration time of rainfall rate as the most ideal integration time for rain attenuation prediction (Mandeep et al., 2007). Nevertheless, long-term rain statistics of rainfall rate distributions are provided at longer integration times (5, 10, 30, 60 min) around the world. Researchers have taken proxy procedures to cover this matter by introducing several methods for converting rainfall rates from a longer integration time into the corresponding 1-min distribution. The proposed conversion methods, such as those used by Segal (1986), Burgueno et al. (1988), Chebil and Rahman (1999), and Joo et al. (2002), and the EXCELL Rainfall Statistics Conversion (EXCELL RSC) model (Capsoni and Luini, 2009) and the Lavergnat and Golé model (1998), are discussed in this paper. This paper is different than Mandeep et al. (2007) as the research was conducted for a different location to test the validity of the model due to latitude and longitude. The location for this paper is known as the "The Land Bellow the Wind" as it is just below the typhoon and monsoon belt.

2. Conversion method

The conversion principle can be classified into two different approaches. One approach is using the conversion process carried out in Jung et al. (2008), which uses equivalent rainfall rates. A second approach is based on the same probability of occurrence. This paper used the latter approach for the conversion purpose due to its simplicity compared to the former approach. Numerous representations of an equal-probability method are as follows:

2.1. Segal method (1986)

The Segal method was developed based on a specialized database of high-resolution rainfall records prepared at the Communications Research Centre (Segal, 1986). As with all tipping-bucket rain gauges, the inherent integration time was an inverse function of the rainfall rate. The rainfall records were acquired from approximately ten years of daily tipping-bucket rain gauge charts for each of the 47 stations in Canada. These 47 stations were deliberately selected to offer a fair pattern for numerous climatological and physiographical systems. Segal (1986) proposed the conversion method expressed as the proportion of the equally probable rainfall rate as follows:

$$\rho_\tau(P) = R_1(P) / R_\tau(P) \tag{1}$$

with the conversion factor, $\rho_\tau(P)$ expressed as power law

$$\rho_\tau(P) = aP^b \tag{2}$$

where $R_1(P)$ represents the rainfall rate in a 1-min integration time with the possibility of occurrence P, $R_\tau(P)$ is the rainfall rate in τ-min integration time, and the parameters a and b are the regression coefficients that are derived from the computed rainfall data.

2.2. Burgueno et al. method (1988)

Burgueno used the long-term quasi-instantaneous rainfall rate data series from Barcelona, Spain, recorded by a Jardi rain gauge over 49 years to establish the conversion method. The Jardi rain gauge recordings are continuous chart recordings of the rainfall rate with a 10 s response (Burgueno et al., 1988). This defined that the rainfall rate is quasi-instantaneous. The prediction of the attenuation due to rainfall in a radio link, however, may not require quasi-instantaneous rainfall rates because rapid fluctuations of point rainfall rates do not translate directly to rapid attenuation fluctuations. Burgueno et al. (1988) want to build a straightforward and globally applicable equation for the rainfall rates' relation of 1- and τ-min integration time of the long-term rainfall events in Barcelona, Spain. The equation applied the principle of direct power-law fit.

$$R_1(P) = aR_\tau^b(P) \tag{3}$$

$R_1(P)$ and $R_\tau(P)$ are the precipitation rates with a sampling interval of 1 and τ min, respectively, which contain a percentage of time, P, and a and b represent the conversion variables.

2.3. Chebil and Rahman method (1999)

Chebil and Rahman introduced an experimental technique for estimating the precipitation rate conversion element by using the conversion process from 60- to 1-min integration time in Malaysia based on 7 years of rainfall incidents from 1991 to 1998. Sixty-minute rainfall data were gathered for the Malaysian Meteorological Service (MMS) for 35 sites at several locations in Malaysia. The rain gauge used to measure the rainfall is the Casella type tipping bucket with a sensitivity of 0.5 mm per tip. The daily deviation of the convective disturbance rain event is considered in the development of this approach, and the stratiform rain event, which produced higher rainfall, was not considered. The Chebil and Rahman approach is based on the modification on the conversion factor of the Segal method by introducing the additional variables of the exponential principle. This parameter increases the flexibility of the method in order to enable an absolute adequate to the computed value of the conversion component. The conversion of 60- to 1-min rainfall distributions were expressed as:

$$\rho_{60}(P) = R_1(P)/R_{60}(P) \tag{4}$$

where $\rho_{60}(P)$ is expressed as a mixed Power-Exponential Law.

$$\rho_{60}(P) = aP^b + ce^{(dP)} \tag{5}$$

where the percentage of time is represented as P, the precipitation rate in 1-min and 60-min integration time to the percentage of time is declared as $R_1(P)$ and $R_{60}(P)$, respectively, and the regression variables are represented as a, b, c, and d.

2.4. Joo et al. method (2002)

Based on 2 years of rain events in Korea (July 1998 to May 2000), rain rate distributions with various integration time data (1, 10, 20, 30, 60 min) were obtained. Raindrop data were acquired by utilizing a Optical Rain Gauge (ORG) at ETRI in late May, 1998. There are two ways to derive the prediction distributions. The first is to average the rain distribution over the measured period by using two annual readings. The second uses an analytical rain event distribution throughout the entire measured durations. Joo et al. suggested using the entire rain event distribution to estimate rainfall rate data (Joo et al., 2002). Joo expressed the conversion method in terms of 1-min possibilities of occurrence. The conversion of time probability from τ-min to 1-min rainfall rate is as follows:

$$P_1 = aP_\tau 10^{[b\ \exp(-t/24.28)]} \tag{6}$$

where the possibility of a specified amount of rain rate at 1-min and τ-min happening are given by P_1 and P_τ, respectively, t represents the sampling interval (min) for the rain gauge, and a and b are defined as regression coefficients.

2.5. EXCELL RSC model

The EXCELL Rainfall Statistics Conversion (EXCELL RSC) model (Capsoni and Luini, 2009) was developed using a physical foundation based on the simulated movement of synthetic rain cells. The conversion of rainfall was obtained using a virtual rain gauge according to the local mean yearly wind velocity, which was extracted from the ERA-15 database on a global basis. The rainfall model is described by the original EXCELL model (Capsoni et al., 1987) that reproduces the local rainfall statistic means of an ensemble of synthetic cells with rotational symmetry and exponential spatial distribution of rain intensity, R (Capsoni and Luini, 2009). The conversion of the 1-min rain rate for monthly (m) variation, $P(R)_1^m$ to $P(R)_T^m$, for various integrations of time T are considered for different stratiform (v_{strat}) and convective (v_{conv}) cells, which take into account the actual space-time evolution of rainfall.

$$v_{conv} = v_{700} / k_1(T) \quad \text{and} \quad v_{strat} = k_2(T) v_{conv} \tag{7}$$

v_{700} is the mean velocity relative to the isobar 700 hPa, and $k_1(T)(>1)$ *and* $k_2(T)$ (<1) are the reduction factors dependent on the rain gauge integration time, T.

2.6. Lavergnat and Golé model (1998)

The Lavergnat and Gole (LG) model introduces a conversion factor h to scale both the rain, R_T, and the probability, P_T, as follows:

$$R_1 = R_T / h^{\alpha} \tag{8}$$

$$P(R_1)_1 = h^{\alpha} P(R_T)_T \tag{9}$$

where: $h = 1/T$ and $a = 0.1609$. a is described as a coefficient that was determined empirically. The difference in the model is that LG used a conversion factor operating in both rain rates as well as probability values.

The model was based on data collected using a disdrometer that analyzed fine temporal structure of rain rather than its intensity aspect. The total measurement was for 2 years in Paris, France.

3. Data collection

3.1. Measurement system set-up

The measurement system was set up in Kuching, Sarawak at Latitude 1.56° N and Longitude 110.34° E for 5 years of data collection. A tipping bucket rain gauge with a capacity of 0.2 mm for each tip associated to a time stamp with a 0.1 second resolution. The collecting surface has an aperture area of 400 cm^2 with a precision of ±1% at 1 liter/hour. The tipping bucket has measures from 5 mm/h minimum, up to 300 mm/h maximum. The gauge produces a voltage pulse whenever a tip occurs and is supervised through a workstation that traces the computer time when a tip is occurring. The data logger then stamped the results at 0.1 second durations and balanced the total value over a 1 minute interval.

3.2. Measurement analysis

Tipping bucket rain gauges are specially designed to log the time of occurrence of a tip, whereas the precipitation rate at that specific moment is not recorded. Consequently, the time-series plot has to be extracted into a Microsoft

Excel file for translation purposes. The translation process from the amount of tips in that particular time into rainfall rate (mm/h) can be carried out as follows:

$$R = \frac{60 \cdot 60 \cdot C}{T} \tag{10}$$

where C is the tipping bucket capacity and T is the time between two tips in seconds. A total of 1440 samples, which alias to 1440 minutes per day from 00:00 to 23:59, are used for analysis. From this analysis, where 1 tip is equal to 0.2 mm per minute, the lowest rain rate that can be obtained is 12 mm/h.

3.3. Local random errors

Tipping buckets are subjected to local random errors such as losses due to wind, wetting, and evaporation. The largest of these errors are wind-induced undercatch. According to Ciach (2003), these errors are called 'local', which differs from other errors related to insufficient spatial sampling.

Wind-induced errors are caused by air flow blockage leading to lighter rainfall particles that fly away before reaching the rain gauge. According to Servuk (1996), wind-induced losses could be as much as 2 to 15%. The World Meteorological Organization (WMO) has suggested a generic method for data adjustment of wind-induced error, which is given by:

$$Pk = k(Pg + \Delta P1 + \Delta P2 + \Delta P3) \tag{11}$$

where:

k = adjustment factor for the effects of wind field deformation

Pk = the amount of precipitation caught by the gauge collector

Pg = the measured amount of rainfall in the gauge

$\Delta P1$ = the adjustment for the wetting loss

$\Delta P2$ = the adjustment for evaporation

$\Delta P3$ = trace rainfall

Wetting and evaporation errors occur when rainfall totals are collected in the inner walls of the gauge and evaporate without being recorded. The wetting loss depends on the type of rainfall, which could be a liquid, a solid or mixed. It is also dependent on how frequent the rain gauge has been emptied, the material of the rain gauge funnel and the geometry of the rain gauge (Legates et al., 1997). Servuk (1974) developed an equation, P_w, for calculating the wetting loss

$$\Delta P_w = \bar{a}M \tag{12}$$

where

$\bar{a}$ = the empirical coefficient of the average wetting loss per rainfall event

M = the number of rainfall event

Evaporation losses are based on the delay between a rainfall event and its measurement. These losses vary by rain gauge type and time of year. Although evaporation losses are small, they have been encountered by Servuk (1974).

$$\Delta P_e = i_e \tau_e M \tag{13}$$

where

i_e = evaporating intensity (mm/h)

τ_e = duration of evaporation

M = frequency of measurement

The magnitude of i_e differs based on the rain gauge and daily weather conditions at the measurement site. For tipping-bucket gauges, water remaining in one of the buckets may evaporate before the next event, and thus, evaporation losses become more significant (Seibert et al., 1999).

4. Results and discussion

The cumulative distributions rainfall rates for several integration times are plotted and shown in Fig. 1.

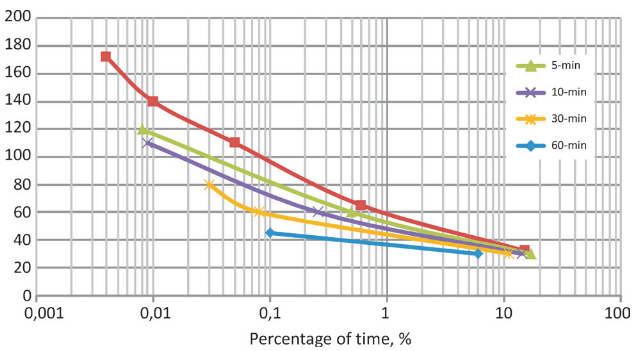

Figure 1. Cumulative distribution of rainfall rates from 2001 to 2010.

Table 1. Summarized regression coefficients for conversion methods.

Integration time (min)	Segal (1986)		Burgueno et al. (1988)		Chebil and Rahman (1999)				Joo et al. (2002)	
	A	b	a	b	a	B	c	d	a	b
5	1.0540	−0.0289	1.3630	0.8814	0.9869	−0.0662	0	14.5400	0.2740	0.6530
10	1.1890	−0.0061	1.8018	0.8775	1.1700	−0.0101	0	17.3000	0.2837	0.8064
30	1.3360	−0.0307	3.1492	0.7551	1.2760	−0.0469	0	19.5300	0.8392	0.7784
60	1.5390	−0.0635	6.4372	0.6170	0.7226	1.2110	2.0880	−1.0440	10.2600	-8.5040

Figure 1 shows that for the same percentage of time, as the integration time increases, the rainfall rate decreases. The rain gauge sampling interval determined the rainfall rate distribution. Therefore, a rainfall-measuring structure having a long sampling time will regularly miss logging the short-range crest in rain intensity. Table 1 summarizes the regression coefficients used for the conversion process determined from the rainfall rate data measured. The regression coefficients were computed to range from $0.004\% < p < 1.0\%$ of time with respect to each integration time. For each conversion method, there is a specific relationship between the 1-min and τ-min rainfall rates. Segal and Chebil and the Rahman method define the relationship as a conversion factor in terms of a power law and a mixed power-exponential law, respectively, whereas Burgueno et al. and Joo et al. describe the relationship as a direct power law and function of rainfall rate, respectively. The curve fitting method had been used to determine the regression coefficient using MatLab software.

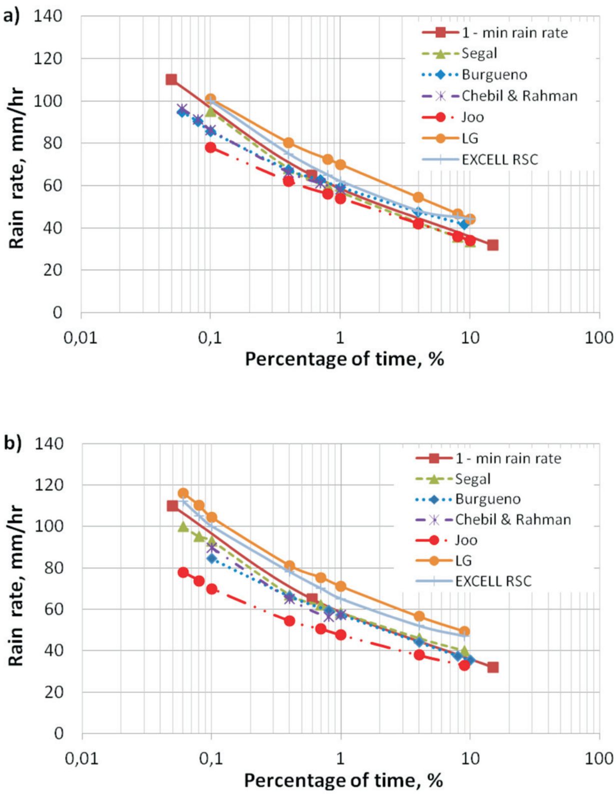

Figure 2. Comparison of (*a*) 5-min, (*b*) 10-min, (*c*) 30-min and (*d*) 60-min converted rain rates.

Figures 2a–d show the plots for 1-min rainfall rates from measured data and converted from several integration times (5, 10, 30, 60 min) using a conversion method. Hourly (60-min) rainfall rates are the most valuable conversion because most meteorological stations only collect hourly data. The converted rainfall rate for various integration times were compared with measured data at various percentages of time. The conversion error can be computed using the following equation:

$$\%\,error = \frac{R_\rho - R_m}{R_m} \times 100 \tag{14}$$

where R_p represents the converted rainfall rate in mm/h from the conversion method and R_m represents the measured rainfall rate in mm/h. The RMS conversion error for several conversion methods has been plotted and is shown in Fig. 3.

The bar graph shown in Fig. 3 shows that the Segal method provides a reasonable overall RMS conversion error of less than 4% for different integration times (5, 10, 30, 60 min). The Segal method agrees well and has recognized several important factors, such as the different integration times of the rain gauge

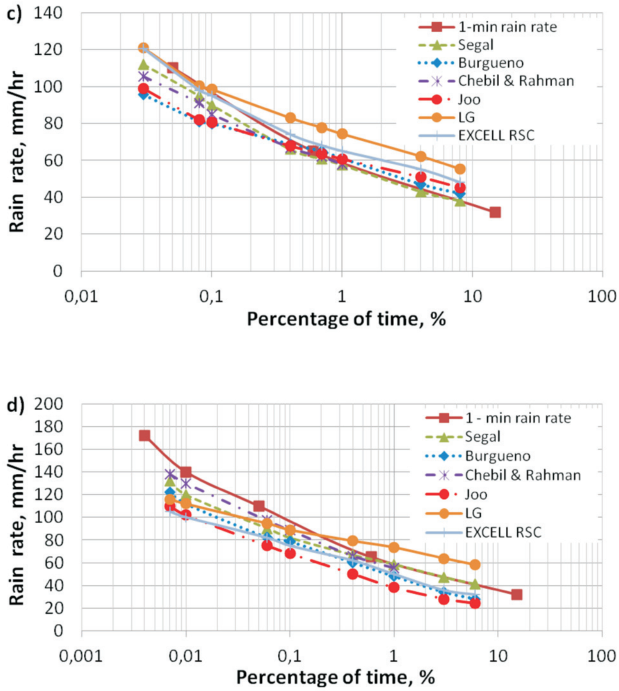

Figure 2. Continued.

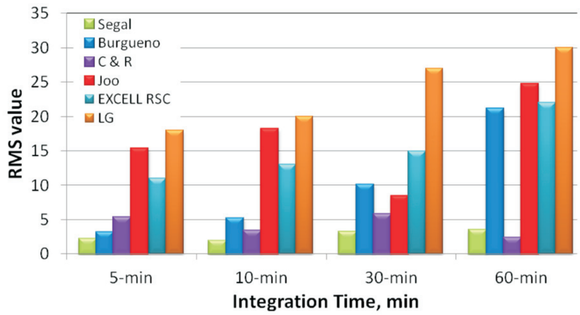

Figure 3. RMS conversion errors for various conversion methods.

and the percentage of time that the particular rainfall rate occurred, that contributed to the distribution effects when this method was developed. The Burgueno et al. method is not applicable for the transformation of 30- and 60-min intervals because it yields an RMS conversion error above 10%, but for rainfall rates with an integration time of 5 and 10 min, this method yields an acceptable range of RMS conversion error. This is because Burgueno et al. considers the development of rain droplets and the relative amount of stratiform rain with respect to convective rain.

The Chebil and Rahman method produces a feasible overall RMS conversion error of below 5% for different integration times. Chebil and Rahman's method is based on the modification of the Segal method by using the rainfall rate data in Malaysia and Singapore in order to match the tropical region. The regression coefficients of this method are established from thunderstorm activities where stratiform-type rainfall, which yields higher prediction errors, is not taken into account. The Joo et al. conversion method generated an outrageous RMS conversion error for various integration times and is not advisable to use for conversion in the USM campus. This is because the Joo et al. technique came from a very short measurement interval, which may correspond to a statistical extreme. The yearly deviation of an instantaneous rainfall rate distribution is not recognized by Joo. The methods of Joo et al. are believed to have been established from stratiform rain events, which are believed to be less practical in Malaysia with high rainfall rates. The EXCELL RSC model performed better than the LG model, and both models exhibit consistent and stable RMS values for prediction error. The EXCELL RSC model performed best at the 5-minute integration time compared to the other conversion time. The LG model has a change in the RMS values from 18% at 5 minutes integration time to 30% at 60 minutes integration time. The coefficient a suggested by LG limits the prediction accuracy of the model. To improve the accuracy of the model, coefficient a needs to be calculated for sites in climatic regions other than those studied in this paper.

5. Conclusion

In this paper, several rainfall rate conversion processes have been carried out for various integration times using cumulative rainfall distribution for 5 years. As an overall result, the Segal (1986) method was found to be the best method for the conversion process involving rainfall rates with various integration times with the lowest RMS conversion error. Because of this, the Segal (1986) method is suggested for other tropical sites.

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SAŽETAK

Empirijske metode za konverziju razdiobe intenziteta oborine s nekoliko dužih intervala na 1-minutni intenzitet u Maleziji

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Brzi razvoj sustava radio komunikacija, a što je naročito izraženo u razvijenim zemljama, potaknuo je inženjere na istraživanje frekvencijskog pojasa iznad tzv. K_u pojasa. Naime, radiokomunikacijski sustavi koji rade u frekvencijskom pojasu iznad K_u-pojasa (10 GHz) podložni su prigušenju u oborinskim uvjetima. Stoga je predviđanje atenuacije radio signala korištenjem 1-min intenziteta oborine od velike važnosti. Međutim, za razliku od razdioba intenziteta oborine za duža kumulacijska vremena, razdiobe 1-min intenziteta nisu široko dostupne. Stoga je neophodna metoda konverzije za predviđanje distribucije 1-min intenziteta oborine za različita kumulacijska vremena. U ovom radu je prikazano nekoliko metoda konverzije kao što su metode Segala, Burguena i suradnika, Chebila i Rahmana, Jooa i suradnika, te EXCELL RSC i LG metoda. Metoda Segala daje ukupnu srednju kvadratnu pogrešku (Root Mean Square Error – RMS) ispod 5% za različita kumulacijska vremena i pokazuje se prikladnom za upotrebu u Maleziji.

Ključne riječi: kumulacijsko vrijeme, razdioba intenziteta oborine, metoda konverzije, koeficijent konverzije, mikrovalovi

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